Modal Analysis of the Persian Music Instrument Kamancheh: An Experimental Investigation

F. Saati Khosroshahi[a], K. Sepahvand[b], M. Güttler[b], K. Pourtahmasi[c] and S. Marburg[b]
[a]Özyeğin University, Department of Mechanics, 34788 Istanbul, Turkey
[b]Universität der Bundeswehr Munich, Werner-Heisenberg-Weg 39, 85579 Neubiberg, Germany
[c]Wood and Paper Science and Technology Department, Faculty of Natural Resources, The University of Tehran, 4111 Tehran, Iran
ferina.saati@ozu.edu.tr

The kamancheh is an originally Persian bowed string instrument which is a spike fiddle with a membrane closing the sound box. The resonance box is usually made of elm wood and includes no sound holes; therefore, it is novel in terms of acoustical analysis. In this paper, it is further assumed that the membrane processes isotropic properties subjected to some pre–stress. Experimental modal analysis is performed on the instrument with focus on the membrane's vibration across a frequency range from 150 Hz to 3.2 kHz. An in–house measurement setup is formed by a Polytec PSV400 scanning laser vibrometer while the bridge sitting on the membrane of the kamancheh is directly excited by means of electromagnetic shaker with periodic chirp signal. The dynamic responses measured by the vibrometer are next treated in a modal post–processing stage in order to extract the modal data, i.e. natural frequencies, mode shapes and damping with a high level of accuracy. The experimental data are employed to compare with a finite element model from literature to have a first image of the membrane behaviour.
Keywords: Kamancheh, experimental modal analysis, membrane, FEM modeling

1 Introduction

Analysis of Musical instruments goes back a few decades in history and until now, several studies have focused on the luthiers and their historical instrument-making techniques. The main goal is to recognize the instrument's speciality and the characteristics of different variations. Various models of instruments are created to perform a numerical analysis which can then be used after validation to improve the sound quality by changing the instrument structure. Major issues to be addressed are: how can we create a good sound? In which way does the timbre change when minor alterations occur in a single instrument? How different are the products of different instrument-makers? And is what they claim as important as it should be?

The traditional Persian fiddle *Kamancheh* combines of two Persian words: *Kaman* means bow and *-che(h)* means little. The sphere-like body, with a membrane on the end of the body (see Fig. 1), is the most popular fiddle in Persian musical culture. The instrument is a bowed spike fiddle originating from old Persia which is unrivaled among the other studied instruments due to the shape of its resonance box. Traditionally Kamanchehs had three silk strings until the beginning of the 20th century, but modern ones have four strings which are commonly tuned as E-A-E-A or G-D-A-E depending on the music played. The frequency range is similar to violins. In this instrument, the bridge sits directly on the membrane and therefore transfers the constant tension and vibration from the strings exited by the bow to the membrane. Hence, the membrane has a role similar to the soundboard in guitar and violin. However, a note played by Kamancheh is totally different from the note played by violins which makes the instrument a special one to Persian. Various forms of this instrument are widely used in the classical music of Iran, Armenia, Azerbaijan, Uzbekistan, Turkmenistan. However, there is no reported scientific attempt found in the literature to analyze the Kamancheh by any means (acoustical, physical, modal or even a time-frequency signal representation). The Kamancheh makers have historically followed what their masters had experimentally taught them, no scientific data has been derived and to the best knowledge of the authors this paper is a first attempt of a thorough analysis process.

Kamancheh's neck is commonly made from wood of walnut tree. Its sound box is made of a hard wood which is generally chosen to be one of the following: red elm, maple or mulberry. The box is either made by hand (treated as a complete artwork) or made by forming machines. It is also either made as a box of one whole piece or made from several pieces glued together. The membrane is typically fish (without scales) or deer skin or tissue of a cow's stomach and is therefore a biological tissue. The Kamancheh we used for the current analysis has the following characteristics: box of red elm wood, neck of walnut wood, membrane of fish skin and metal as soundpost.

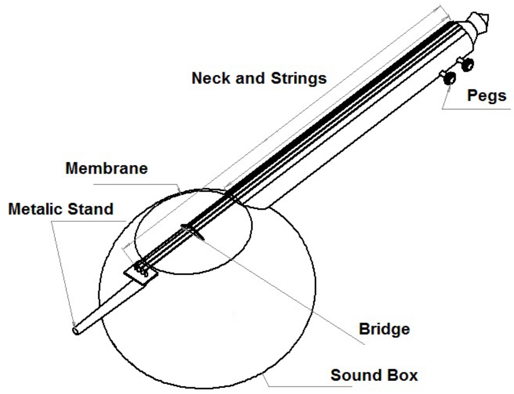


Figure 1: Schematic of one type of Kamancheh showing the parts and their names

2 Introduction to membrane analysis

On the membrane instruments, there exists prior work which has been done on various drums, percussion, tom-tom, timpani and banjo according to which the membrane is the most important member in the vibration (refer to Tronchin et al. [1] as an example). In this work, the subjective is to present a study of the modal characteristics of Kamancheh and it is focused on the experimental results. String vibrations are transmitted via the bridge onto the membrane. A possible excitation of the structure is due to the contradiction of the strings length while vibrating. Consequently, the vibrations of the whole instrument generate acoustic traveling waves through the air. As it was reported by Elejabarrieta et al. [2], the top plate plays a crucial role in the sound radiation of a classical guitar at high frequencies and the mode shapes are strongly dependent on the bridge and fan bracing design. In this paper we show that the acoustic properties of kemancha is dominated by the skin as well as the bridge; while the soundbox is mostly there to create the enclosed air cavity and to make the boundary condition of the skin. In figure 2, a vibration diagram of different parts of Kamancheh is displayed. As seen in this diagram, the vibration created by string is transmitted via the bridge and neck. The bridge directly vibrates the membrane. The membrane and neck on the other hand, transmit the vibration to the sound box. The cavity inside the sound box is vibrated via the vibration of all the three parts mentioned. External air is also vibrated in the end.

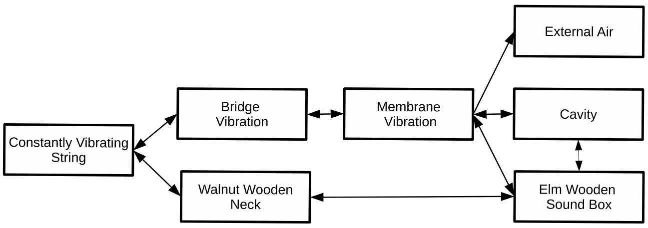


Figure 2: Vibration of different parts of Kamancheh

In the current study, we have shown that the vibrations of neck and the box are in scale of 0.01 to 0.001 of the membrane vibrations. This led us to further simplify the modal investigation as a starting point. Hence, in order to understand the basic physics of modal behavior, the effects of structural complications including fluid-structure interaction were neglected for first order estimation which then could be reliable in a reasonably accurate way. The case simplifies to a pre-stressed elastic circular membrane which is fixed with tension at its boundaries. In order to solve the membrane problem, first we should see which equations it is behaving upon. According to Gonçalves et al. [3], the analysis of membrane mechanics is an important topic in nonlinear continuum mechanics. In particular, the study of hyperelastic membranes under finite deformations, such as elastomeric membranes and most biological tissues, is a rather challenging subject, and in such cases, elasticity in the fully nonlinear range must be employed. The first developments in this field are collected in the classical work by Green and Adkins [4].

Without any prior data of the membrane used in Kamancheh, it may be worth considering whether any mode localizations expected can be a consequence of geometric or material nonlinearities. However, according to Gonçalves et al. [3], the mode localization tendency can be explained more simply as inherent to the small-amplitude, linear elastic behavior of a membrane. Preliminary theoretical results can therefore be obtained based on linear membrane theory that suggest increasing localization of membrane vibration as a parameter combining excitation frequency, tension, and distance from excitation source is increased. According to Gonçalves et al. [3], the vibration of a membrane can be considered as the two-dimensional generalization of the vibration of a string, or as the degenerate case of plate vibrations. A membrane by definition has vanishing flexural stiffness. Consequently, the spread of bending information is weak, but is dependent on the tension, frequency, local curvature, and damping. Gonçalves et al. [3] have considered the effect of tension and frequency only. The membrane material is also considered to be homogeneous, isotropic. Derivation of the governing equations for the linear (small strain, small rotation) transverse of the undamped vibration of circular membrane is amenable to either Newtonian or Lagrangian methods (Jenkins et al. [5]). The most widely used form is the special case wherein the inplane shear stress is zero, and the initial tensile T is constant and the same in all directions. That is

$$T\nabla^2 w + p = \rho h \frac{\partial^2 w}{\partial t^2} \tag{1}$$

In which ∇^2 is the Laplacian operator, p is the external load, ρ is mass density per unit volume of the material, and h is the membrane thickness. The equation is solved where all edges are fixed. It is well–known that the neutral frequencies are function of T, ρ, h and boundary conditions and tendency for mode localization can be explained using linear theory (Jenkins et al. [5]). In particular, when the region of excitation is much smaller than the membrane diameter, oscillations become more and more localized around the region of excitation as the excitation frequency increases for a given tension. In addition, when membrane size is finite, the resonant oscillations also tend to become increasingly localized with increase in frequency for a given tension, and this effect is amplified with reduction in membrane tension. The theoretical results also show that the localization tendency appears to be due to the inherent stiffness inertia related dynamics of membranes. The cavity-backed membrane also appears in literature in Rajalingham et al. [6] as example, where the multimodal approach is used and membrane is modeled as a dynamical system of two subsystems. It is shown that the vibrational modes of the system can be categorized into three groups (Rajalingham et al. [6]): (1) the modes for which the vibration is predominantly in the membrane, and consequently the corresponding system frequency is close to that of the isolated membrane; (2) the modes where the vibration is pronounced in the cavity and the corresponding system frequency is near that of the closed-end cavity; and (3) the modes in which the vibration is significant in the membrane as well as the cavity. In this case the system frequency is neither close to the membrane nor to the closed-end cavity frequencies.

3 Experimental setup

The setup consists of a mount to hold the instrument, dampers at the supports to reduce the external vibrations, a shaker to apply a certain profile of periodic excitation, a force transducer to measure the force at the point of application, and finally a metal bar to connect the force transducer to the shaker. The instrument is mounted similar to the way it is actually played. Setup details can be seen in Fig. 3. Laser Scanning Vibrometer is put in 50 cm distance from the bridge point where the excitation occurs. The force transducer touches the bridge slightly on one of the strings (second string, A tuned). Figure 3 shows the various parts of the setup.

The shaker excitation was applied as white noise and the time signal was windowed by hanning window method to make sure that the signals are fitted to zero at the start and end points of each period. Number of points in mesh created (figure 4) was 110. The number of measurements per point was 5 and the average of them were used for each. White noise was used due to the fact that using a bow, the string of a Kamancheh goes under a continuous impulse (stick slip periodic) excitation and in this type, all modes and frequencies are excited.

Experimental modal analysis is performed on the instrument with focus on the membrane's vibration across

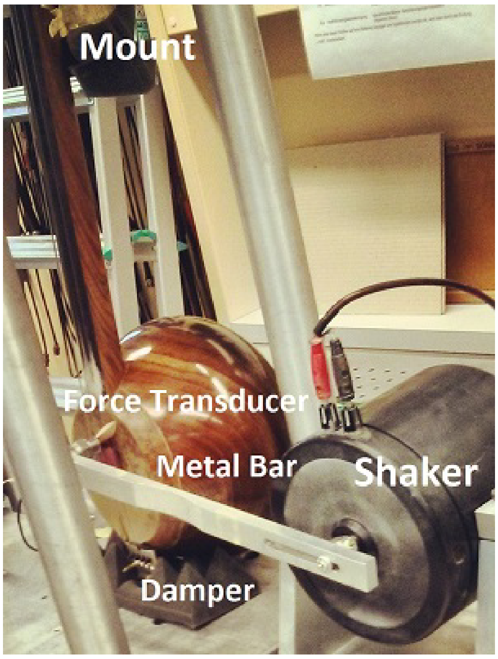


Figure 3: Various Parts of the Setup

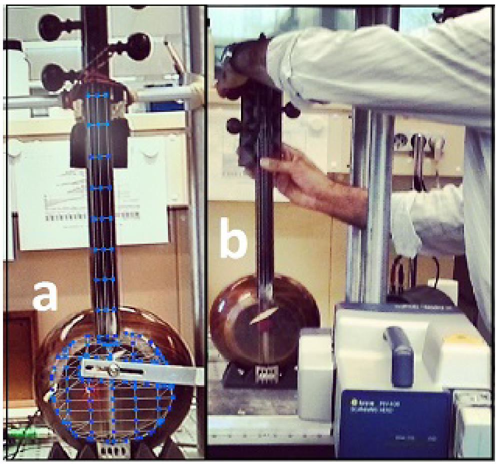
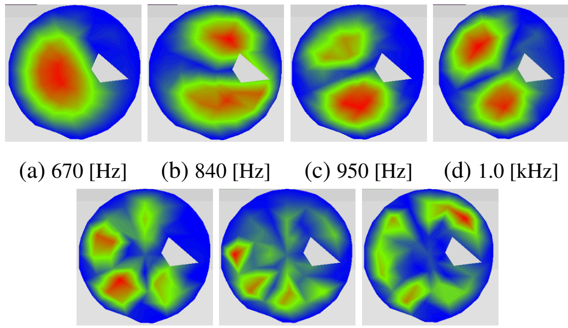


Figure 4: The Laser Vibrometer and the created mesh; a. View from the camera, b. normal view while mounting

a frequency range from 150 Hz to 3.2 kHz. The resolution of FFT was 2 Hz with 1600 FFT lines. Natural frequencies and vibration shape modes of the membrane were then derived in the frequency range. These shapes are mostly used for their lowest vibration. As it can be seen in Fig. 5, the first 7 vibration modes possess have the natural frequencies: 0.67, 0.84, 0.95, 1.0, 1.5, 1.97 and 2.17 kHz, respectively. These are the plane results; meaning that, they have been derived from operational deflection shapes. The Modal Phase Colinearity (MPC) was profited to investigate the independence of eigenvectors. According to MPC estimation, values of 0.75 or higher are assumed to be independent enough to be eigenvectors. The chosen modes were of MPC=0.9 or higher, which means that modes are actually recognized correctly.

4 Preliminary Results and Discussion

As expected, the membrane vibrates significantly at higher scale than the structure which can at first guess be



(a) 670 [Hz] (b) 840 [Hz] (c) 950 [Hz] (d) 1.0 [kHz]

(e) 1.5 [kHz] (f) 1.97 [kHz] (g) 2.17 [kHz]

Figure 5: The first 7 vibration mode shapes and the corresponding natural frequencies of the membrane measured by laser scanning vibrometer.

also due to the sphere-like shape of the sound box. In order to investigate this, 49 nodes were created on the membrane and 44 nodes on the rim of the membrane (structure of sound box). Post-processing was done in ME'Scope software with details seen in table 1. Each was averaged by FRF squared (velocity squared is kind of estimation in terms of Equivalent Radiated Sound Power). Averaging of squared FRFs of Rim and Membrane was done separately . Linear and dB scale of the squared FRFs are plotted in Fig. 7 and Fig. 8. Difference of the two were plotted in Fig. 6. Pressure exerted from the bridge to the membrane was measured by means of pressure sensitive foils that was put between the bridge and the membrane. In order to do this, the strings were loosened first. The pressure applied onto the membrane was found to be 0.4 MPa. Deflection of the membrane due to the force from the strings via bridge was also found to be 2mm. After reassembling, the strings were tuned again by E-A-E-A in order to get the right tension.

Table 1: ME'Scope Spreadsheet data block

Measurement type	FRF
X axis spacing	Uniform
X axis Units	(Hz)
Y axis type	Magnitude
Y axis DOFS	Averaged
X axis Units	$(\frac{m}{N.s})^2$

The first three modes are seen as the most efficient ones and the ones which in higher frequencies, mostly the high harmonics of them are playing part. This is due to the fact that they have higher amplitude and are stronger to act in higher frequencies in which higher force is needed. For any finite element model to be created, the spatial dependency of the membrane must be taken into account. Hence, isotropic material assumption may work only for the two first modes only. The first three modes are as comes in a, b, c, d and e in Fig. 5, while the first three modes found for Kamancheh's membrane are depicted in Fig. 5-f, g and h. The mode shapes match suitably.

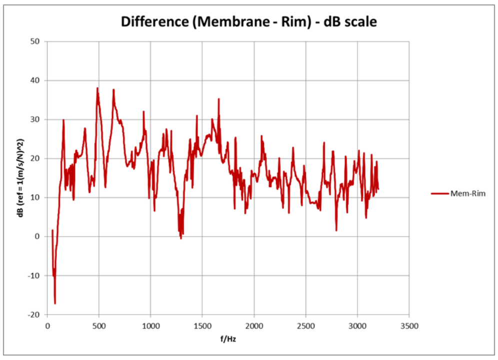


Figure 6: difference (membrane-rim) dB scale

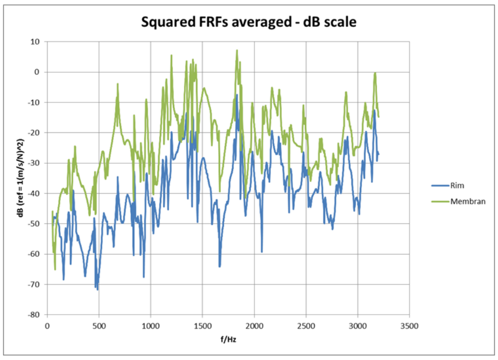


Figure 7: Squared FRFs averaged- dB scale

5 Conclusion

In this experimental work, the Persian-rooted musical instrument Kamancheh was investigated. The musical instrument under study and the literature of membrane analysis has been briefly introduced first. It has been demonstrated from modal tests that the membrane experiences a vibration of two to three scales bigger than the instrument neck and the sound box. For that reason, the analysis and the measurements are only conducted for the membrane. Seven natural frequencies and vibration modes were found to be the modes of the instrument within the frequency range of 150 Hz to 3.2 kHz. The first three modes were presumably the more effective ones. Details of the force exerted onto the membrane via the bridge was measured using pressure sensitive foils and the deflection of the membrane was also found. The agreement between the experimental and FEM results from literature were discussed. However, efficient investigates are required to identify the most effective vibration modes.

Acknowledgment

The authors gratefully acknowledge Mr. Arslan Hazerti for providing the sample instrument for the experiments.

References

[1] Tronchin L., Buttazzoni A., Tarabusi V.,“On the sound production of the timpani”, *WSEAS Conference Proceedings, Venice, Italy,* (2004).

[2] Elejabarrieta M. J., Ezcurra A., Santamaria C., ”Coupled modes of the resonance box of the guitar”,*J. Acoust. Soc. Am.* **111**(5), 2283-2292 (2002)

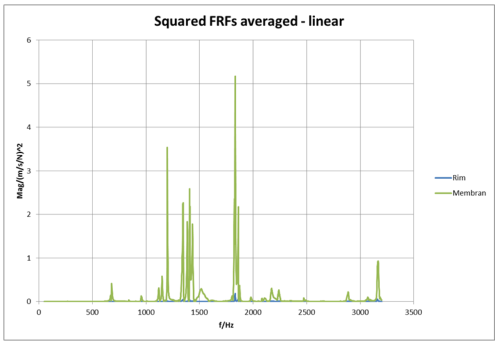
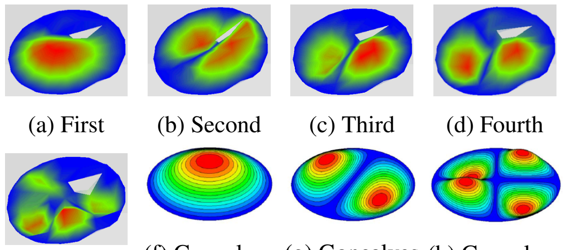


Figure 8: Squared FRFs averaged- linear



(a) First (b) Second (c) Third (d) Fourth

(e) Fifth (f) Gonçalves frist (g) Gonçalves second (h) Gonçalves third

Figure 9: Most efficient modes of the membrane measured by laser vibrometer compared with three most important modes from FEM simulation of Gonçalves et al. [3].

[3] Gonçalves P. B., Renata M. S., Pamplona D., ”Nonlinear vibrations of a radially stretched circular hyperelastic membrane”,*Journal of Sound and Vibration* **327**(1), 231-248 (2009).

[4] Green A. E., Adkins J. E., “Large Elastic Deformations and Non-Linear Continuum Mechanics”, *Oxford University Press*, Oxford, 1960.

[5] Jenkins C. H. M., Korde U. A., “Membrane vibration experiments: an historical review and recent results”, *Journal of Sound and Vibration* **295**(3), 602-613 (2006).

[6] Rajalingham C., Bhat R. B., Xistris G. D., “Vibration of circular membrane backed by cylindrical cavity” *International journal of mechanical sciences* **40**(8), 723-734 (1998).